TECHNICAL OPTIONS FOR DISTRIBUTED HYDROGEN REFUELING STATIONS IN A MARKET DRIVEN SITUATION

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1. Abstract

Many studies have already addressed the tradeoffs between the various hydrogen refueling stations, but few studies have worked on how a station should be managed on a day by day basis, in a market driven situation. No data are already available since the existing H2 stations are still in the permitting phase, and there are no big fleets refueling now. But parameters such as vehicle daily load profile, seasonality in demand, station electricity load, could have an influence on station design. Especially in the case where the hydrogen is produced locally at the station and stored as a gas, these problems could be a major hurdle if not considered prior to building the station: the combination of the storage, reformer compressor and dispenser must be sized for the most demanding day we can expect: but many station have a seasonality and a vehicle profile that will vary depending on the day of the week. There is also a tradeoff between the reformer size and the storage size: the bigger the reformer, the smaller the storage.

This is very different from a regular gasoline station, where the gasoline is brought by truck: there we simply meet the peaks of demand by bringing in more trucks. This could in fact make us reconsider the tradeoffs between the H2 pathways: a liquid storage has been said to be more expensive than a gaseous one, but a liquid storage should offer much more flexibility for demands with important variations. The transient response should be much better than with a reformer that usually needs to work at a steady state. The problems that arise with liquid H2 storage are much more understood since this technology is closer to what we know with gasoline (both are brought by trucks and stored liquid). For an onsite production and a gaseous storage, the problems and governing rules are completely different.

My study has evaluated various configurations and strategies for addressing the seasonality.

My study has also tackled the energy station, assessing how adding a fuel cell to a station might improve the results. This calls for a good understanding of the station electricity needs.

I have also studied the station in a market buildup scenario and compared various technical solutions such as sizing the station to achieve a 100% capacity use in a future year and running it at lower loads; using a fuel cell to improve station use; following demand by adding capacity (i.e. reformer, compressor, storage) from time to time.

2. A study of the seasonality

I have accessed data from TOTAL refueling stations network in France to study the seasonality. My study has led me to divide these stations in two groups: town stations and highway stations. I show here a typical station monthly sale profile for each type.

My fist station is located in Paris, as shown in Figure 1, and qualifies as *a town station*

Figure 1: a location for a town station

The monthly sales of gasoline for this station are shown in Figure 2:

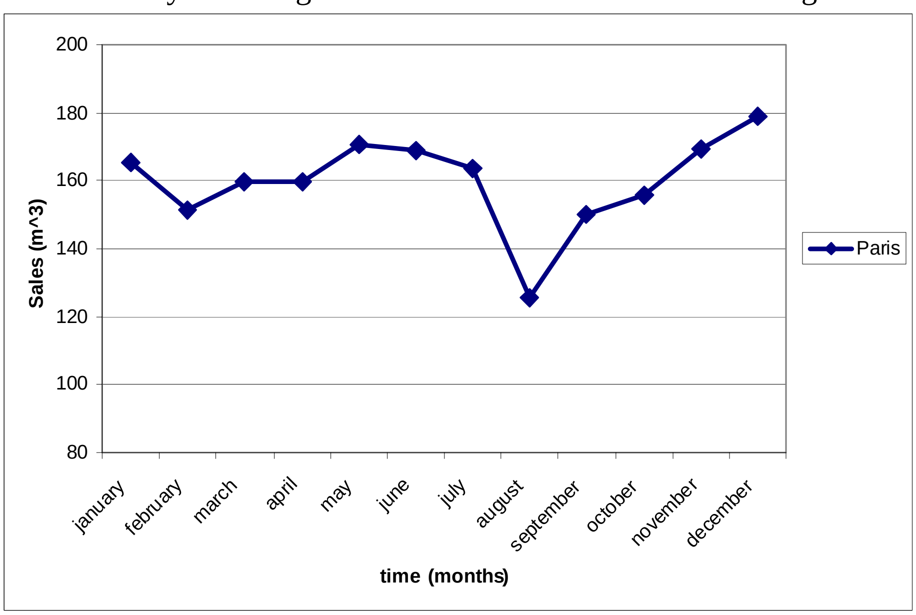

Figure 2: the monthly sales of a town station

This shows that a town station has a low seasonality, the sales level only significantly decreasing in August, when many people are on vacation.

My second station is located on a highway, outside any city, as shown in Figure 3, and qualifies as *a highway station*

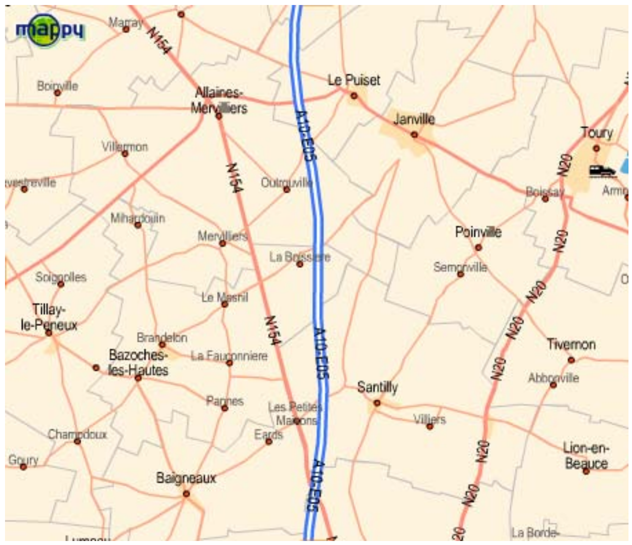

Figure 3: a location of a highway station

The monthly sales of gasoline for this station are shown in Figure 4. Note that this graph excludes professional sales for trucks and road professionals; this is because in the early stage it is improbable that the trucks would run on FCs.

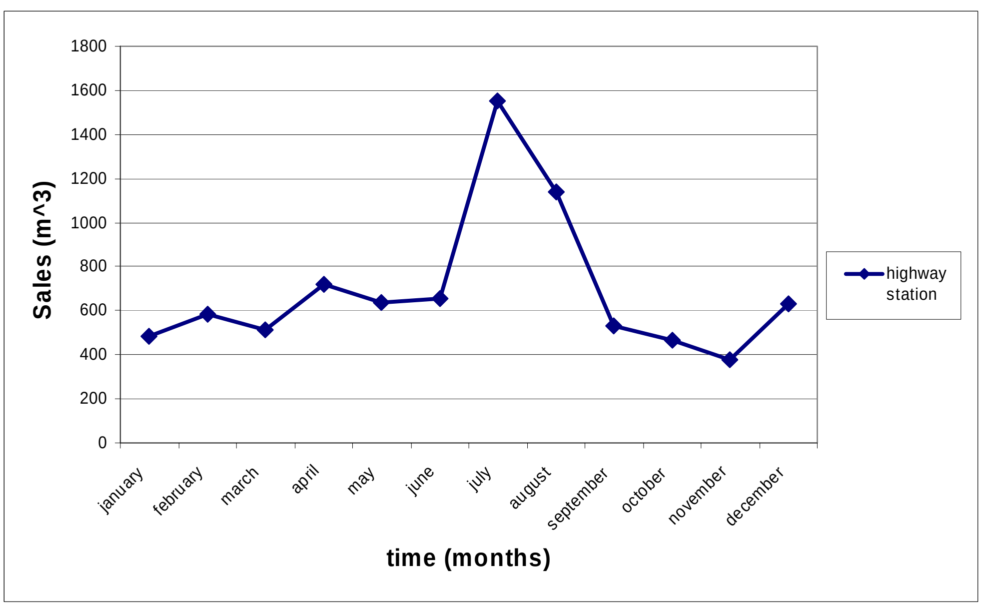

Figure 4: The monthly sales of a highway station

This shows that a highway station has a high seasonality, the sales level surging in July and August, when many people are traveling for vacation. This seasonality could be a significant hurdle for the reformation option.

3. Reformer station VS LH2 station

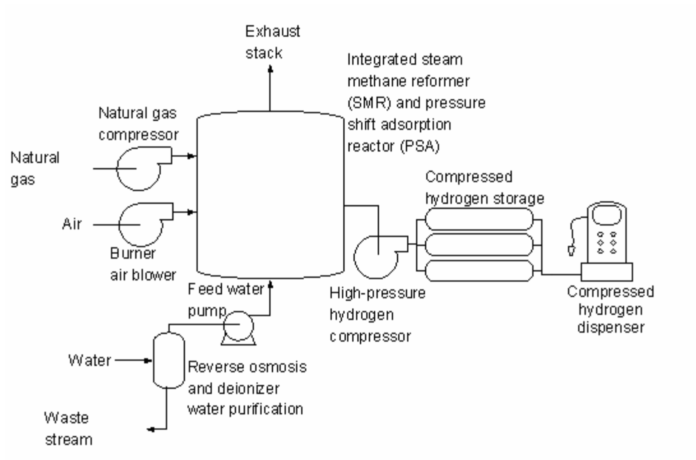

Figure 5: A sketch of the reformer station

The figure 5 is a scheme of the reformer station. The reformer station main advantage is that it produces low cost hydrogen, as has been estimated in former studies. However, using such a technology also has drawbacks: the capital cost is significantly higher than for the LH2 station, which increases the financial risk; this technology asks for a good vehicle demand understanding, to store the right amount of hydrogen; at the present state of technology, SMR reformers (the most efficient ones) have long transient answers and cannot be turned down completely. Overall, the system is not flexible, and thus more adapted to well understood and constant demands.

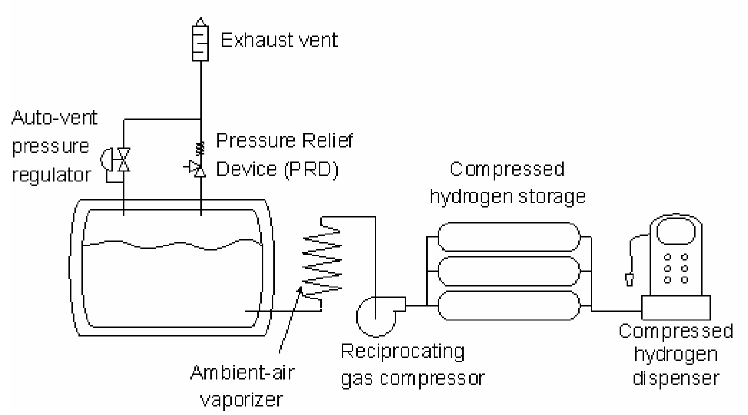

Figure 6: A sketch of the LH2 station

The figure 6 is a scheme of the LH2 station. The main hurdle of the LH2 station in the high energy use to liquefy the hydrogen, leading to high unit cost, around 2 to 3$/kg to produce the hydrogen. However, the LH2 station has advantages: its design is straightforward and more compact; the capital cost is less than the reformer station; since this system does not have a *capacity limit* (in terms of kg H2 produced/hour), it can handle much more easily seasonality and uncertainties in demand.

4. A study of the reformer station

My study has assessed the influence of the seasonality on the station yearly net income.

The seasonality has proved to have an important influence on the town station: by taking it into account, the yearly net income decreased from 35% to 60%, depending on the assumed vehicle demand at the station. 35% referred to a case where the FCVs would penetrate 100% of the market: the vehicle demand at the station would then be 300 vehicles/day. 60% referred to a case where the FCVs would penetrate 2% of the market and where 10% of the stations would be converted: the vehicle demand at the station would then be 60 vehicles/day. The H2 sell price is set at 5$/kg for all my study.

The seasonality has proved to have a very important influence on the highway station: by taking it into account, the yearly net income decreased from 70% to 102%, depending on the assumed vehicle demand at the station. The vehicles demand at the station were, respectively, 1700 vehicles/day and 340 vehicles/day (this demand refers to the highest demand in the year, which occurs during the weekends of July).

I have also addressed the tradeoff between the reformer and compressor size, on the one hand, and the storage size, on the other hand. To do so, I have introduced a parameter named “%boost”, and defined as follows:

$$compressor\_flow(kg/hr) = (\%boost * H2\_demand\_hour) + \left[(1 - \%boost) * \frac{\sum_{day} hourly\_H_2\_demand}{24} \right]$$

Table 1 describes the tradeoffs for 2 cases: %boost=0% or 100%

mode	%boost=100%	%boost=0%
System flexibility	high	low
Reformer and compressor size	big	small
Storage size	small	big
Reformer runs at a steady state	Within an hour	Within a day

Table 1: System profile for 2 %boost

My study has shown that:

- for the town station, the influence of the %boost over the yearly net income is weak. For vehicles demand below 98 vehicles/day, it is best to run the station at %boost=0%.
- For the highway station, the %boost has a strong influence on the yearly net income. For vehicle demand above 36 vehicles/day, it is best to run the station at %boost=100%. This means that the reformer would be able to change its output every hour, which is not possible at the present state of technology. This also means that we can precisely predict the amount of hydrogen every hour to store this amount in the storage. Probability laws on vehicle demand would probably lead us to store a bit more to be sure to satisfy demand.

5. Comparing the reformer station results with the LH2 station

I have tried using a LH2 station with the same assumptions, and compared the yearly net incomes. The table 2 and 3 below shows at what price the liquid hydrogen should be bought at the liquefaction facility so that the LH2 station breaks even with the reformer station. The results are showed as a function of the station distance from the liquefaction facility. Studies have showed that liquefied hydrogen would cost a minimum of 2 to 2.5 $/kg.

distance from LH2 facility (km)	H2 sell cost to break even with a reformer working at %boost=0 ($/kg)	H2 sell cost to break even with a reformer working at %boost=100% ($/kg)
0	1.64	1.77
50	1.51	1.64
100	1.38	1.54
150	1.29	1.46
200	1.25	1.38
250	1.18	1.32
300	1.12	1.25
350	1.06	1.20
400	1.01	1.14
450	0.96	1.09
500	0.91	1.05

Table 2: LH2 break even costs for the town station

This table shows that the needed LH2 costs are too low for the LH2 station to compete with the reformer station.

For town stations, the reformer option remains the best

distance from LH2 facility (km)	H2 sell cost to break even with a reformer working at %boost=0 ($/kg)	H2 sell cost to break even with a reformer working at %boost=100% ($/kg)
0	2.88	2.01
50	2.82	1.95
100	2.77	1.87
150	2.72	1.85
200	2.69	1.82
250	2.66	1.79
300	2.62	1.75
350	2.59	1.72
400	2.55	1.68
450	2.52	1.65
500	2.48	1.61

Table 3: LH2 break even costs for the highway station

This table shows that, for the highway stations, the LH2 station can be the best option if the reformer cannot achieve %boost=100%.

This shows the importance of studying and understanding the ability of the reformer to run transient. Also, understanding how much we could reduce the LH2 price is important.

6. A study of the energy station

Studies have suggested using a fuel cell in the refueling stations to optimize the reformer use. When not enough cars show up and there is unused capacity, the fuel cell would run, using the available hydrogen.

My study has assessed various technical options for the fuel cell:

- “reformer optimization”: the fuel cell is placed before the compressor and storage. None of the equipment is resized. The fuel cell is sized to run on whatever is available, allowing a reformer use of 100%.
- “Steady state”: the fuel cell is placed before the compressor and storage. The fuel cell must run at a steady state all time (constant output), meaning that the reformer needs to be resized
- “load following”: the fuel cell has to load follow the building needs. It is not a constant load, so the reformer has to store the hydrogen is the storage. The fuel cell is placed after storage. The reformer, compressor and storage need to be resized.

The electricity is sold according to French electricity prices, that is around a mean value of 4.5 c$/KWh. The figure 7 below shows an example of the station yearly net income for various fuel cell sizes, for 2 of these scenarios.

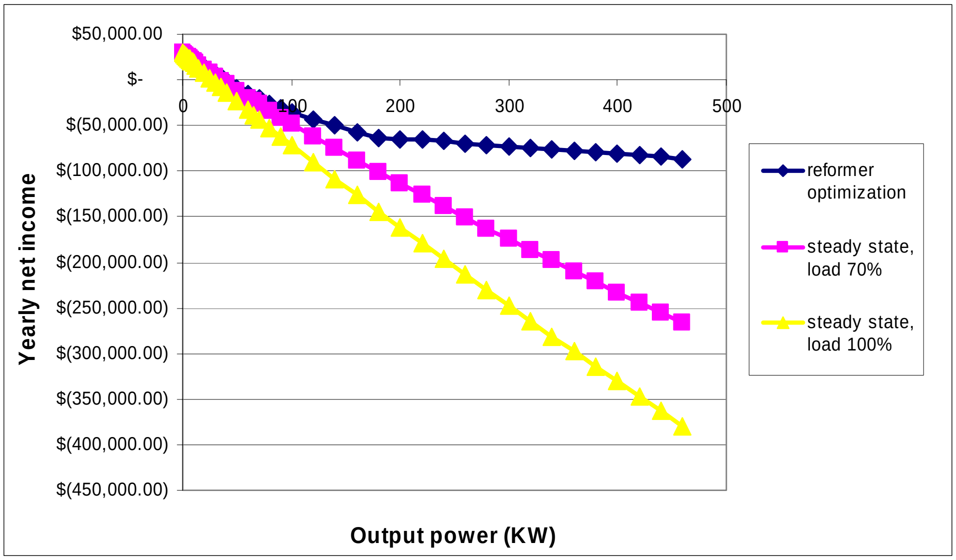

Figure 7: Yearly net income of the system working with various FC sizes, as a function of the FC size

The load of 70% or 100% refers to the fuel cell load as a percentage of maximum.

I have not found any configuration (even with cogeneration) where adding a fuel cell is beneficial. A quick calculation shows that, with French electricity and natural gas prices, we actually lose money on a variable cost basis (without taking into account the capital cost). My study has shown that, in order to break even, we would need to sell the electricity at rates between 20-30 c$/KWh (small fuel cells) and 10-15 c$/KWh (large fuel cells). This is between 2.5 and 7 times the market price for electricity!

I have done a study over the European countries, looking for favorable conditions. The natural gas and electricity prices have been extracted from the Eurostat database (http://epp.eurostat.cec.eu.int). They depend of the country but also of the power subscribed.

The figure 8 below shows, in plain line, the needed natural gas/electricity price ratio needed so that the marginal solution of adding a fuel cell gives a 10% IRR (internal rate of return). I have called “u” this ratio. u is adimensional, the natural gas price and electricity price were expressed in c$/KWh. In dashed lines are the u ratios for various European countries. The lower the u, the better for the fuel cell solution.

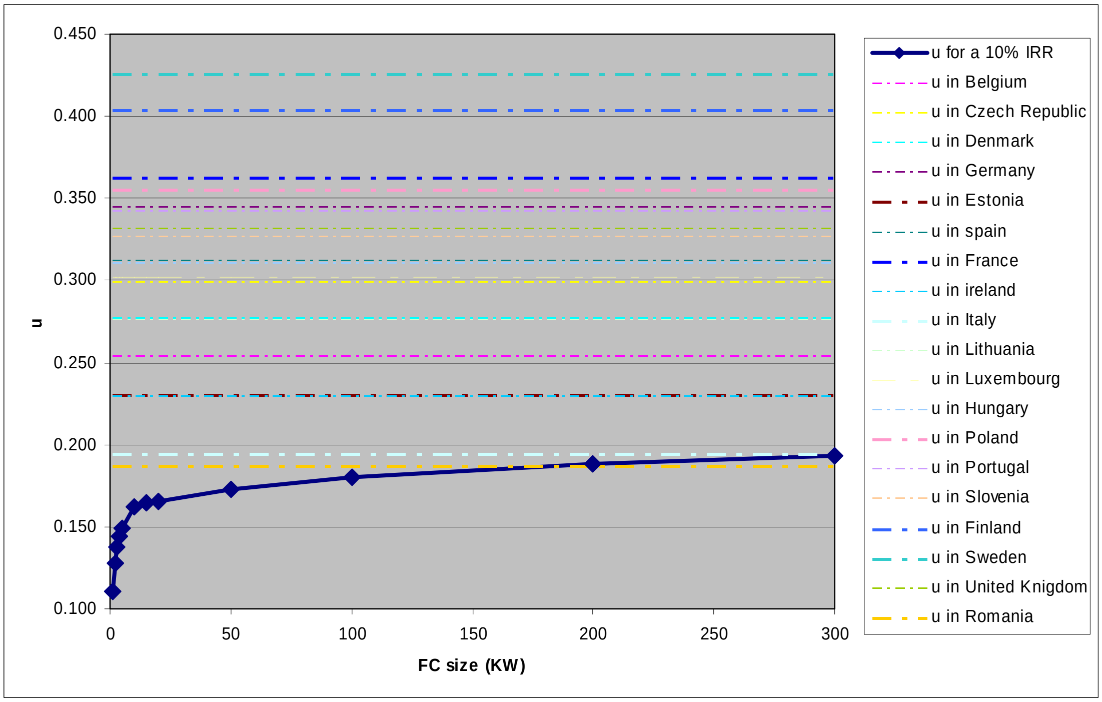

Figure 8: Natural gas/electricity price ratios for a 10% IRR and in various European countries

We can see that only Romania and Italia can achieve a 10% IRR, and for large fuel cells. The simulations I have run show that, in the best case (large production discount factors achieved, large refueling stations), Romania, Italy, Ireland, Estonia and Belgium could achieve a 10% IRR[2].

7. Introduction to the market buildup problem

The market will go into a phase of building up before saturating. This can be also seen as a “seasonality” if we define it broadly as an inefficiency leading to less use made of the available capacity. I have built a model to assess the influence of such a market buildup on the station results. I was also interested in defining a strategy to address this buildup problem. I wanted to answer several questions: when should we invest in a refueling station? For what demand should we size it? Is it interesting to invest in several steps rather than one (buy more capacity when needed)?

I will assume a market buildup following a Gompertz curve as in figure 9. My time reference is based on this curve. I define year 1 as being the first year where the demand for hydrogen appears (at a level of 2% of maximum demand). The market buildup will last for 20 years. I define start_year as being the year when

[2] Some European countries have not been analyzed because of non availability of data on natural gas and/or electricity prices

we build the station on this scale; end_year as being the year we size the station for.

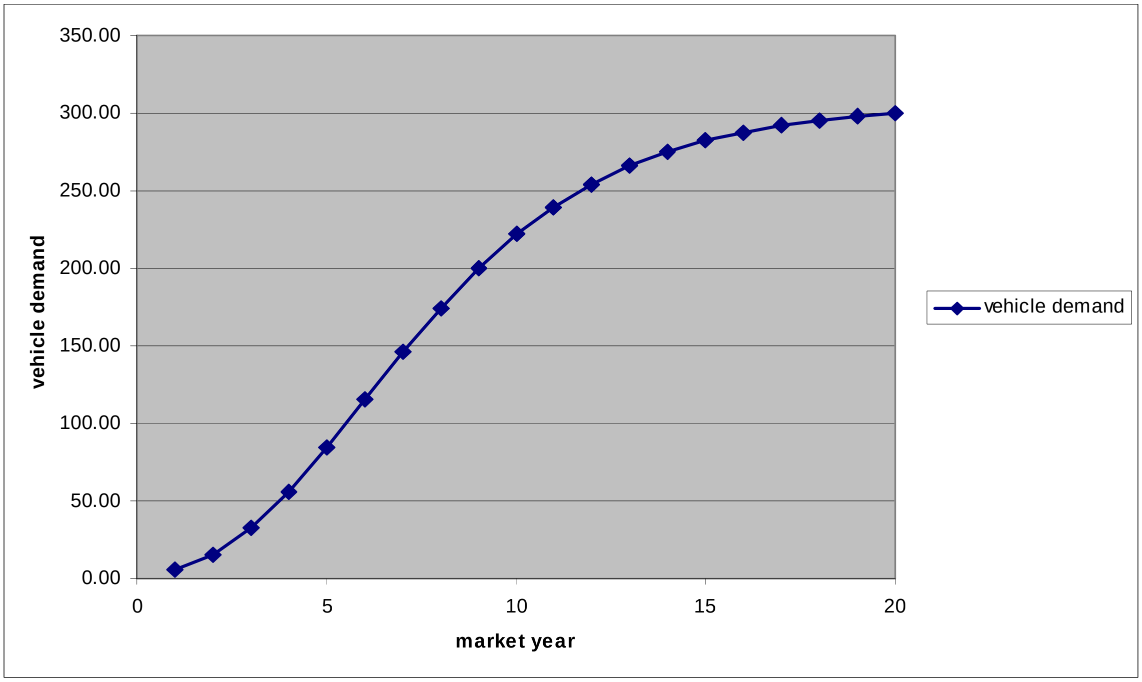

Figure 9: A market buildup for an end demand of 300 vehicles/day

8. A station without a possibility of reinvestment

In this case, I allow only one investment in equipment (reformer, compressor, storage). Once built, it is not possible to allow a reinvestment in another set of equipment during the station lifetime.

The figure 10 shows the IRR for a reformer station, with an end demand of 300 vehicles/day in year 20. It covers all the possible start_years and end_years. Notice that my model assumes a station lifetime of 15 years.

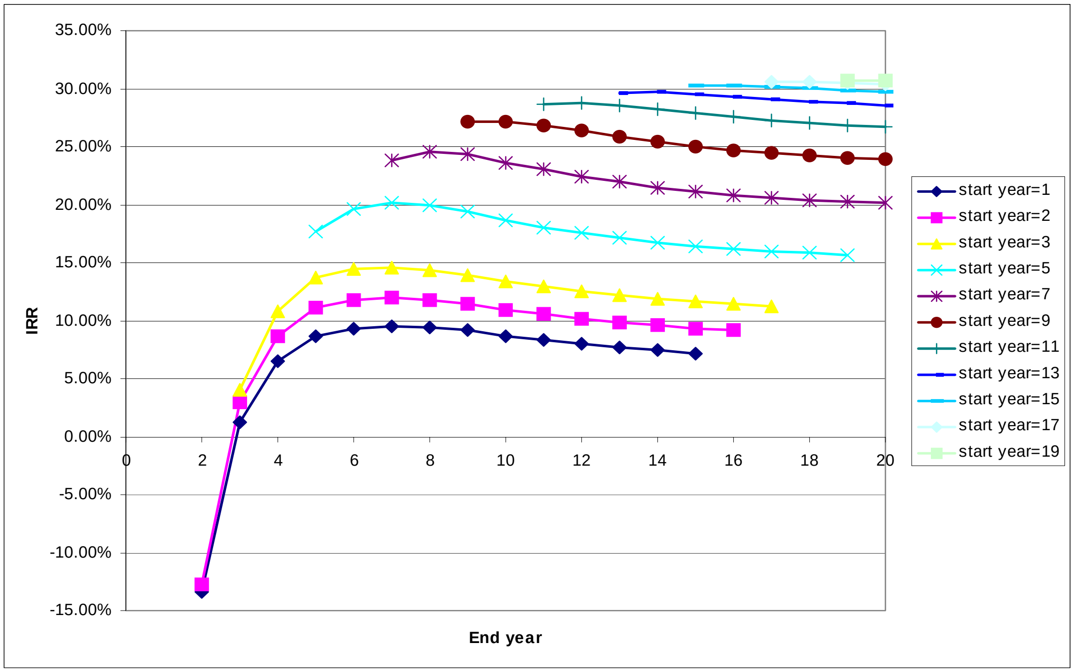

Figure 10: IRR results for various start_year and end_years

Each dot represents a totally different simulation, since the X axis represents the end_years. Therefore, the X axis is NOT a time axis. For instance, the far right dot of the deep blue curve shows the global lifetime IRR of a station built at start_year 1, and sized for end_year 15.

This brings several comments:

- Of course, it is always best to start as late as possible (but is this acceptable if we want to satisfy the consumer?)
- More interesting, this graph shows that it is not beneficial to anticipate too much. There is an optimum for the IRR that is usually for end_year between 1 and 5 years after start_year. If we anticipate the demand more than that, the IRR starts decreasing slightly, as we less use our available capacity since it takes more time to fully use it.
- With an end demand of 300 vehicles/day, it is possible to achieve a 10% IRR

Another try with an end demand of 60 vehicles/day has showed the same trends, but it is then much more challenging to reach a 10% IRR. Only by starting after year 9 can we achieve a 10% IRR.

9. Using a fuel cell as a non permanent way to optimize the capacity use

I have assessed the idea of using a fuel cell to fully use the reformer capacity while the demand builds up. The fuel cell would be used a lot during the first years, then its use would decrease as more vehicles come to refuel. The model has shown again losses associated with the fuel cell use. The electricity produced would need to be sold between 12 and 25 c$/KWh, depending of the fuel cell size, to break even. This is still too high to be acceptable.

10. Investing in capacity in several steps

There, I have offered the possibility to invest in equipment (reformer, compressor, storage) in several steps, which allows better following of the vehicle demand and lessening the inefficiencies from not using available capacity. On the other hand, buying smaller equipment deprives us from the economies of scale and is possibly more complicated to set up.

Table 4 and figure 11 show the result of the reformer station, for various number of steps realized at a constant interval, for an end demand of 300 vehicles/day. The start_year was 6, the end_year 20.

	IRR	cumulated result at market year 20
one step	25.37%	$ 8,343,226.80
two steps	27.82%	$ 8,207,286.07
three steps	29.22%	$ 7,925,426.64
four steps	30.03%	$ 7,638,797.11
five steps	30.16%	$ 7,097,477.70

Table 4: IRR and cumulated net income for various steps, 300 vehicles/day

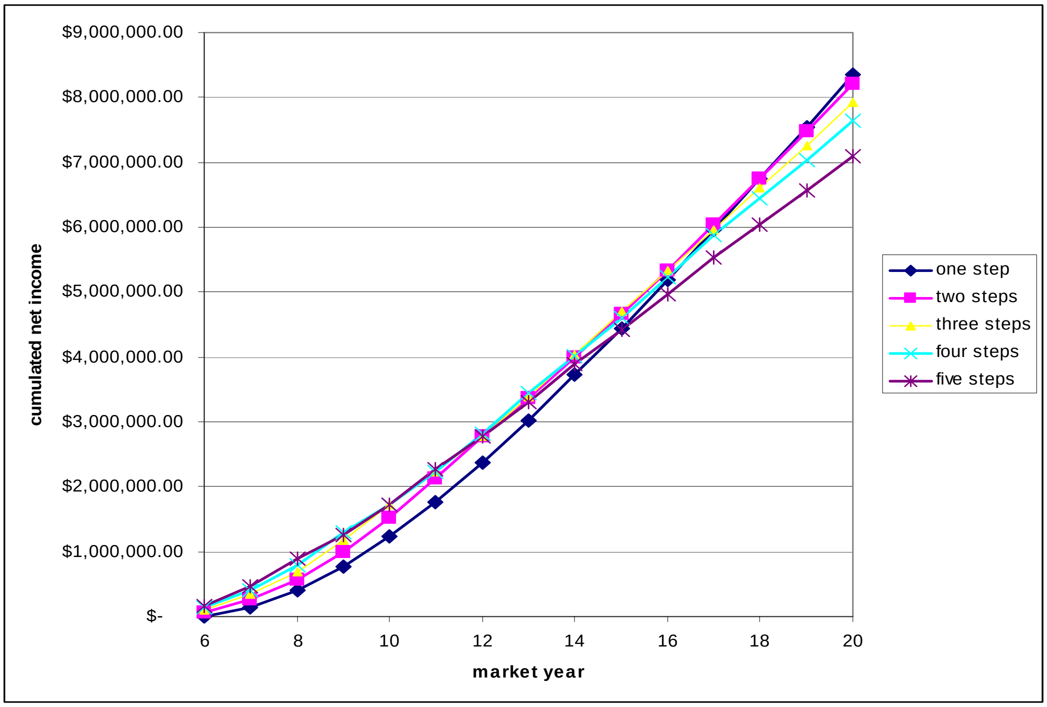

Figure 11: cumulated for various steps, 300 vehicles/day

As we can see, although the result favors the investment in one step, the IRR favors an investment in 5 steps, because the cash flows arrive earlier in that case. Dividing the investment in several steps is better from a financial point of view: less capital is invested in each step, with a closer timeline, which lessens the risk.

Table 5 and figure 12 below show the same results with an end vehicle demand of 60 vehicles/day.

	IRR	cumulated net income at market year 20
one step	12.16%	$ 550,920.58
two steps	9.99%	$ 107,542.99
three steps	6.78%	$ (316,250.50)
four steps	3.20%	$ (698,261.60)
five steps	-3.12%	$ (1,284,698.81)

Table 5: IRR and cumulated net income for various steps, 60 vehicles/day

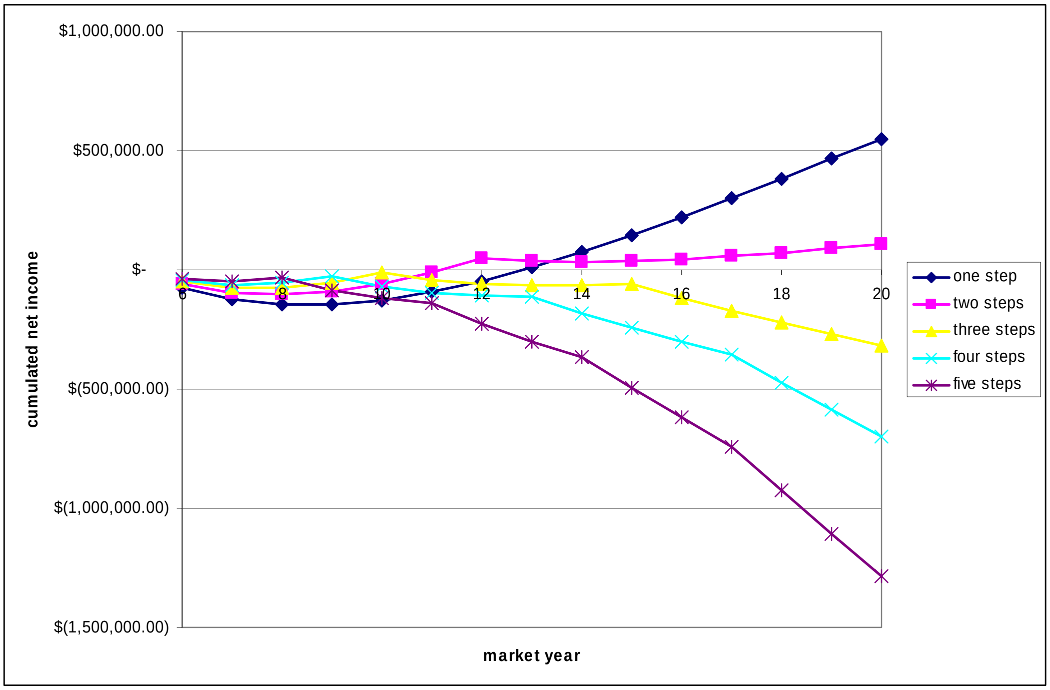

Figure 12: cumulated for various steps, 300 vehicles/day

With less favorable conditions, it becomes better to invest in all the capacity in one step, at the beginning. This is explained by the fact that a set of equipment starts losing money during the first years of its use, before eventually breaking even as its use grows with more vehicles refueling. When we add steps, we lessen the benefits from the second phase but keep the important losses from the first phase!

11.Defining a strategy for hydrogen refueling stations

Town stations

My study has shown that the reformer station remains the best option for the town stations, because they have rather constant sales during the year. Even a market buildup does not justify a technology shift.

It is improbable that a company will want to anticipate the market much, from 15 to 20 years. The risks of making a mistake on market forecasting are too great; also, such a system would take too long to break even.

My study has shown that it is possible to increase the financial yield of the project by making more steps in the investment if we can be in favorable conditions. Favorable conditions are high demand centers, high hydrogen sell price, low interest rates. Being in such conditions allows to lessen the risk by making more steps and to have a faster break even.

The challenge will be to be in such a favorable situation. To do that, refueling stations in high demand centers should be converted in priority. Demand could be aggregated in several big refueling stations. Also, in cities, a company can play on the number of stations converted, which is another level of flexibility. I advocate converting a first set of refueling stations in high demand centers and forecasting demand for 4-5 years. When the capacity saturates, another set of conventional stations would be converted. To further lessen the price, 2-3 basic sizes could be manufactured. We should seek a modular design where capacity could be added easily by “stacking” another set of equipment. This would allow more flexibility. We would go on until the market saturates.

Highway stations

The highway stations are much more problematic than the town stations:

- They show much more seasonality
- Most of them would have to be converted at once to allow the customer to go everywhere, on the contrary of town stations where we can convert little by little. A possible analogy with electronics is resistances in series VS in parallel.
- The highway stations have more demand, which would lead to consequent storage space in the case of gaseous storage.

For several reasons, I believe that the LH2 station is best adapted to highway stations:

- My study has shown that the seasonality and market buildup would justify a technology shift from reforming to LH2.
- The LH2 storage is more compact and less capital intensive (most of the price is spent on buying the liquid hydrogen and this is an operating cost), thus the risk is less and this solution asks for less available cash.
- The LH2 storage is more compact
- The LH2 storage could be safer and has a longer lifetime, although this should be verified
- Access to highway station by LH2 trucks is easy

The necessary highway stations to cover the network could be converted to LH2 stations all at once. The finances of highway stations will remain more difficult than the town stations anyway.

12. Conclusion

My study has shown the problems associated with all the causes of inefficiency in station use. The station cannot usually be used at 100% of its capacity. This leads to decreased results. My study has assessed various ways to improve or solve these inefficiencies:

- using a fuel cell is never beneficial
- using a LH2 station is useful in the case of highway stations
- Dividing the investment in several steps in the market buildup case is interesting if we can maintain favorable conditions (high demand, high H2 price)…

All these considerations are important for station design and should be seriously considered prior to converting a refueling station to hydrogen.

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